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DESIGN OF COAST-PHASE PROPELLANT MANAGEMENT SYSTEM FOR TWO-BURN ATLAS-CENTAUR FLIGHT AC-8

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SUMMARY

The propellant management of a full-scale cryogenic storage to support restart of main engines, following an extended low-gravity coast period, was successfully demonstrated for the first time on the Atlas-Centaur flight AC-8 launched April 7, 1966. Vehicle configuration and propellant management techniques conceived for this mission were verified as control of the residual propellants was maintained throughout a 25-minute orbital coast. Disturbances induced in the liquid residuals were suppressed, residual liquid kinetic energies were dissipated, tank pressurization was stable, boiloff gases were vented overboard in a nonpropulsive mode, and the propellants were retained in a settled position to support restart of the main engines.

Definition of the AC-8 propellant management configuration resulted from experience on the AC-4 flight, the first full-scale coast-phase experiment with low-gravity propellant management. This flight significantly revealed that model test results and scaling parameters did not properly account for the interaction between disturbing forces and energy levels peculiar to a full-scale configuration in a near earth orbit. The basic problems were those of controlling residual propellant motion and of discharging the boiloff gases overboard without upsetting the vehicle. The venting problem was corrected by redesigning the hydrogen vent system to inhibit liquid entrainment, to reduce impingement forces of vent gases against the vehicle, and to provide a more equal cancellation of the vent thrust forces. Energy suppression and dissipation of residual propellant motion were controlled by means of baffles and diffusers and a carefully controlled thrust level beyond main engine cutoff.

INTRODUCTION

The Atlas-Centaur flights AC-4 and AC-8 were the first full-scale experiments with cryogenic propellants in an extended low-gravity environment. The results of these

flights have afforded a major contribution to the understanding of the mechanics of coast-phase propellant management. Extensive theoretical studies and scale-model tests (refs. 1 to 6) have been conducted to define the fundamental laws and scaling parameters, but they do not account for the disturbing forces encountered in a real space vehicle. The model tests have also been limited to relatively short periods of low gravity.

The AC-4 flight (refs. 7 and 8) was configured on the basis of the model test results and scaling parameters, but major discrepancies were revealed in that they did not properly account for the interaction between forces and energy levels peculiar to the full-scale configuration. Large liquid disturbances were induced at main engine cutoff, which unsettled and dispersed the propellants throughout the tank. The coast-phase thrust level was inadequate to settle the propellants, and the unsettled propellants were entrained in the boiloff gas at time of venting. The liquid venting produced excessive vent thrust forces, vehicle tumbling, more liquid venting, and eventual loss of over 90 percent of the propellant residual. Consequently, fuel starvation, due to depletion and displacement, prevented restart of the main engines.

Although the AC-4 flight was not completely successful, the results of the flight provided valuable data to redefine the mechanics of the low-gravity propellant management problem. A thorough assessment of these flight results made possible significant configuration changes on AC-8, the next Centaur two-burn mission. The guidelines used to configure the AC-8 vehicle to further explore the low-gravity propellant management problem and to give assurance for completing coast phase and engine restart of AC-8 were as follows:

(1) The alteration of the venting system to eliminate unbalanced vehicle impingement forces by using a balanced thrust vent
(2) The addition of four 50-pound and four 3-pound ullage settling motors operated in an attitude control mode as well as ullage settling mode
(3) The reduction of liquid-hydrogen boost-pump-volute bleed disturbances using a volute-bleed-energy dissipating diffuser developed in parallel with the investigation of the experimental feasibility of eliminating the volute bleed
(4) The reduction of disturbances from the liquid-hydrogen propellant duct recirculation line by design and installation of a diffuser and/or modification of the fuel duct and recirculation line
(5) The investigation of the requirement for the reduction of the energy from the liquid-oxygen boost-pump-volute bleed and bearing cooling flow
(6) The addition of baffles in the liquid-hydrogen tank
(7) The relocation and/or addition of temperature and liquid-vapor sensors inside the tank
(8) The relocation and/or addition of skin temperature sensors
(9) The provision of adequate vent system instrumentation

(10) A modification of the propellant retention motor configuration to ensure adequate thrust, to minimize impingement forces, and to improve thrust alinement with the vehicle center of gravity

(11) Investigation of the feasibility and problems associated with relocation of the triaxial accelerometer on the vehicle centerline

(12) The programing of coast-phase events in the following sequence:

(a) One hundred pound thrust for 100 seconds following main engine cutoff (MECO) for propellant settling

(b) Six pounds of thrust through the remaining 25-minute coast phase to second main engine start (MECO + 100 sec to second MES - 46 sec) for propellant retention

(c) One hundred pounds of thrust from second MES - 46 seconds to second MES, a period slightly in excess of the duration of the liquid-hydrogen boost pump deadhead

(d) The logic for the operation of the vernier engines in items (a), (b), and (c) provided vehicle attitude control with a minimum of 100 pounds of thrust

(13) The appropriate ground testing to support the vehicle configuration

Correlation of the specific propellant management problem areas as they related to the preceding design changes specified for AC-8 have been detailed for discussion into three major areas:

(1) Induced propellant disturbances at MECO

(2) Coast-phase propellant management

(3) Coast-phase attitude control

INDUCED PROPELLANT DISTURBANCES AT MECO

Nature and Magnitude of Disturbances

The propellant disturbances encountered at MECO on the AC-4 flight, which dispersed the propellant residuals throughout the tank, were excited by the following energy inputs as shown in figure 1.

Fuel boost-pump-volute bleed, 102 foot-pounds. - The volute bleed was a 2.0-inch line, which flowed about 300 to 340 gallons per minute back into the liquid-hydrogen tank from the fuel boost-pump inlet. This line provided a bypass back to the tank during pump deadhead operation. During the pump coast down after MECO, it discharged forward into the ullage, and about 23 pounds of liquid hydrogen were returned to the tank. Under conditions of engine firing, the acceleration forces depressed the height of the fluid discharge, but with thrust termination at MECO this stream erupted through the liquid surface and

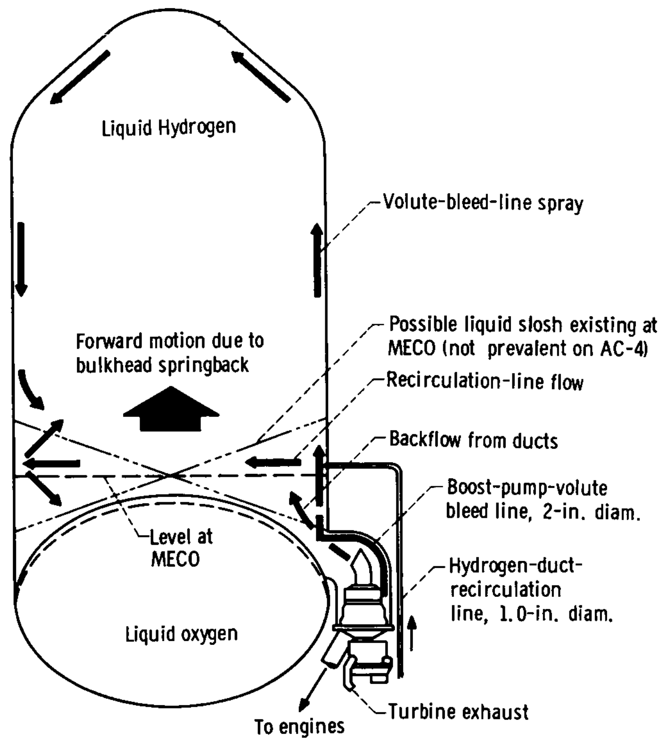

Figure 1. - Residual liquid-hydrogen motion after main engine cutoff for AC-4 flight.

impinged against the forward bulkhead. The total energy input of this geyser was 102 foot-pounds.

Hydrogen-duct-recirculation line, 35 foot-pounds. - The recirculation line used to bleed trapped gas from the lines to the engine inlets prior to lift-off and during boost-pump deadhead enters the tank laterally at station 350. The flow rate at MECO rapidly tailed off from 40 gallons per minute, and a total of about 2.55 pounds were returned to the tank. On AC-4 this discharge entered the tank about 11 inches below the liquid level, washed across the top of the intermediate bulkhead, and curved back around each side. This provided a calculated energy input of 35 foot-pounds.

Regurgitation or backflow from propellant ducts, 35 foot-pounds. - Sudden fuel flow stoppage due to engine shutdown and closure of fuel valves produced a burp, or backflow, into the tank giving an energy input of 35 foot-pounds. Films of flow tests taken during low liquid level shutdowns show the action as a large slug of liquid vapor moving up out of the sump and across the tank at an inclination of about 45°.

Residual slosh energy in liquid at MECO, 35 foot-pounds. - The liquid profile in the propellant tanks on AC-4 was reasonably stable prior to MECO with no measurable evidence of slosh. However, assuming a slosh angle of not more than 10°, the residual slosh energy would be about 35 foot-pounds. The character of this motion at MECO

would be abruptly amplified several hundred times and likely appear as a wave motion up the tank wall and over the top.

Intermediate bulkhead springback, 0.122 foot-pound. - Springback of the intermediate bulkhead at thrust termination produced only slight forward displacement of the fluid, and the calculated energy input was 0.122 foot-pound.

One other possible source of disturbance was asymmetrical thrust tail off at MECO. However, the flight data indicated a specific impulse ΔI_t during shutdown of only 355 pound-seconds, which was well below the 2σ specification value of 514 pound-seconds. This asymmetry did not produce any measurable pitching motion of the vehicle, but it should not be overlooked on future flights.

The net effect of all these kinetic energy inputs (summarized in table I) into the liquid-hydrogen residuals on the AC-4 flight, as verified by the flight instrumentation, produced an initial wave motion up the positive x-axis and over the top, which culminated in a heterogeneous dispersion of propellants throughout the tank. Similar disturbances probably developed in the liquid-oxygen tank but to a lesser extent because of the slosh baffle. This liquid-oxygen behavior, however, could not be confirmed because of the lack of instrumentation.

TABLE I. - KINETIC ENERGY DISTURBANCE LEVELS ON AC-4 AT MAIN ENGINE CUTOFF

Source of disturbance	Energy level ft-lb
Fuel-boost-pump volute-bleed-line discharge	102.0
Hydrogen-duct-recirculation-line discharge	35.0
Regurgitation or back flow through pump	35.0
Residual slosh, no baffles	35.0
Intermediate bulkhead springback	.122
Total energy input	207.122

Reduction of MECO Related Disturbances

The major energy disturbances produced by residual slosh, regurgitation from the boost pump, and return flows through the recirculation and volute bypass lines were greatly reduced by adding baffles and energy dissipation diffusers. The input from the intermediate bulkhead springback, however, was negligible and did not require further action.

The basic design objective of the volute-bleed and recirculation-line energy dissipating diffusers was to reduce sufficiently the kinetic energy level of the fluid streams discharging into the liquid-hydrogen tank so that, under given thrust levels, the liquid would not have sufficient velocity to impinge against the forward bulkhead. Design criteria then established that (1) the required vertical velocity suppression at the liquid surface

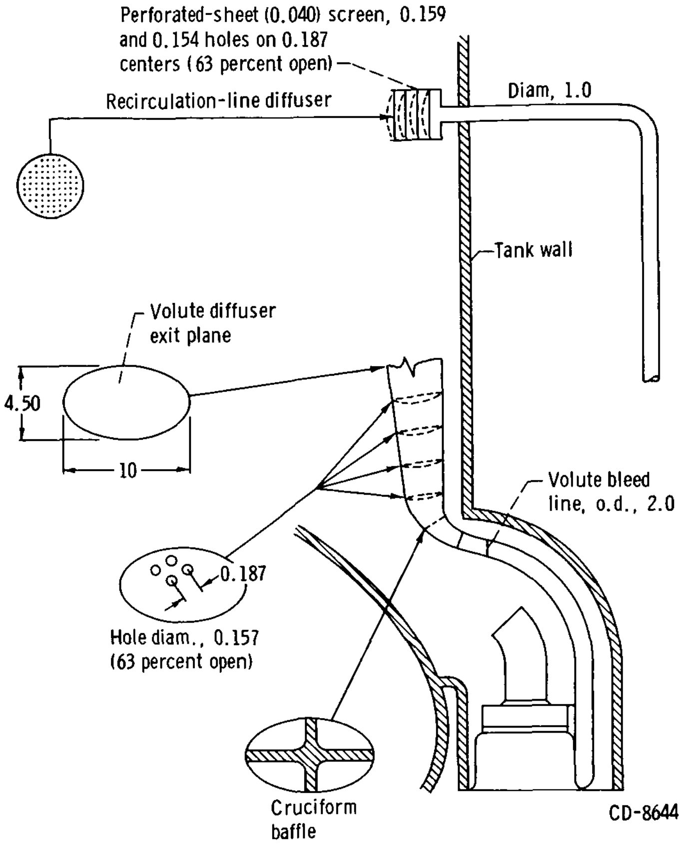

Figure 2. - Volute- and recirculation-line energy dissipating diffusers. Diffuser expansion ratio, 113 to 1. (All dimensions are in inches.)

needed to prevent liquid impingement against the forward bulkhead would be based on using a maximum of 100 pounds of settling thrust applied to the vehicle and that (2) the diffuser must be structurally sound and mounted to existing tank brackets.

The designs of the volute-bleed and recirculation-line diffusers to meet these requirements are shown in figure 2. Perforated baffles in the diffuser are used to dissipate the pump energy by forcing the liquid through a constant enthalpy process. Exit velocities through these lines will, of course, depend on the final flow rates and power level of the boost pump. However, at the AC-4 boost pump flow rate of 340 gallons per minute, the discharge velocity from the volute line would be reduced from about 60 to only 1.5 feet per second. This would result in a fluid stream velocity at the liquid surface of 0.5 foot per second, which, with 100 pounds of thrust (7.4×10^{-3} g), would spout up only 6.3 inches. This would be well below the top of the tank. Reducing the boost-pump power level and volute-bleed flow rate, therefore, to about 65 gallons per minute or less results in the diffuser design being more than adequate.

The recirculation-duct-line diffuser size was limited by the structural mounting brackets on the tank. The exit diameter of the diffuser was 4 inches, and this reduced the radial component of velocity at the liquid surface to less than 0.4 foot per second. Reduction in boost-pump power level also reduced the recirculation-line flow rate following MECO, and made this diffuser design more conservative.

Incorporation of the diffusers markedly reduced the kinetic energy inputs to the liquid-hydrogen tank. Using the AC-4 energy levels as a reference, the volute bleed-line disturbance was reduced from 102 to 1.34 foot-pounds, and the recirculation-line disturbance was reduced from 35 to less than 0.20 foot-pound.

Some uncertainty in the design of these diffusers may exist because of the saturated liquid vapor mixture that is flowing through the lines. However, verification of the dif-

fuser designs under normal-gravity operating conditions was accomplished through a comprehensive test program at the General Dynamics/Convair Sycamore test facility. Design changes or improvements as required were implemented. Supporting tests were also conducted at the Pratt and Whitney E-5 test stand and at the Pesco Company. Scale model tests were conducted at the Lewis Research Center and in San Diego.

Residual slosh energy was not experienced on AC-4, but the possibility of a vehicle entering the low-g coast phase with some slosh cannot be ignored. In this event, the addition of the slosh baffle to dissipate liquid disturbances remaining after MECO, as discussed hereinafter, also served to dissipate pre-MECO slosh energy to a negligible level.

Suppression of the burp or backflow from the boost-pump inlet could also have been affected by a perforated baffle over the boost-pump inlet. However, uncertainty about such a baffle causing adverse influences on the boost-pump performance, by creating a vapor trap during coast phase, ruled this out. This area is still being studied. Any such energy input remaining unchecked at MECO, however, would be subsequently dissipated by the ring baffle.

COAST-PHASE PROPELLANT MANAGEMENT

Propellant management during the coast phase required the ability to control the residual propellant tankage in a posture to support a main engine restart and to permit venting the ullage to maintain tank pressure. The preceding reductions in the MECO induced disturbances were very important, but any energy carryover into the coast phase would still have the potential to produce sizeable liquid excursions that, with very little damping, could persist for long periods. Success of the coast-phase mission then depended on being able to

(1) Dissipate the carryover MECO generated liquid disturbances as rapidly as possible

(2) Suppress the liquid motion well below the forward bulkhead

(3) Settle and maintain the liquid residuals at the bottom of the tank

(4) Vent hydrogen boiloff gas overboard to maintain tank pressurization control, but in a nonpropulsive mode to avoid upsetting the vehicle stability

The design improvements implemented on AC-8 were as follows:

(1) Energy dissipating line diffusers to reduce the MECO disturbances generated by fluid streams discharging into the propellant tanks

(2) Baffles to rapidly dissipate the residual liquid kinetic energy

(3) Programed thrust schedule to settle and retain propellants

(4) A redesigned balanced thrust hydrogen vent system

These design improvements enhanced the success of the AC-8 coast-phase propellant management experiment.

Dissipation of Residual Liquid Kinetic Energy after MECO

The residual kinetic energy from the MECO related disturbances, though reduced substantially (about 77 percent) by the energy dissipating baffles and diffusers, would be transferred to propellant slosh energy at orbit injection. Any remaining energy then would be eliminated as the liquid washed around the tank wall. The period of energy decay however would depend primarily on the initial energy level, the effectiveness of the baffle design, and the level of thrust applied to the vehicle. The new lower residual energy levels effected in the liquid-hydrogen tankage at MECO by the addition of the baffles and diffusers for the AC-8 configuration are shown in table II.

TABLE II. - REDUCED KINETIC ENERGY DISTURBANCE

LEVELS AT MAIN ENGINE CUTOFF

Source of disturbance	Energy level, ft-lb
Fuel-boost-pump-volute bleed (65 gal/min)	1.34
Hydrogen-duct recirculation	.2
Residual slosh with baffles (5°)	10.0
Intermediate bulkhead springback	.122
Regurgitation or backflow through pump	35.0
Total energy input	46.662

The inclusion of residual slosh energy in the MECO transients was conservative. A residual slosh angle of 10° is considered possible without a baffle; therefore with baffles the slosh angle would be reduced to much less than 5°. Assuming then a coalescense of all these energy inputs into slosh energy at MECO would result in a maximum wave velocity of 1.85 feet per second.

Design of the baffle was optimized for the Centaur liquid-hydrogen tank from a parametric analysis of many baffle studies. The final design, as shown in figure 3, was an 8-inch-wide annular ring located at station 333.3 about 3 inches below the nominal liquid level with antiswirl baffle plates spaced uniformly around the circumference. From the damping characteristics shown in figure 4, the baffle position was selected to give a maximum damping ratio of 0.61. For maximum and minimum variations in liquid depths at MECO this damping ratio could be as low as 0.31. These data are based on 1-g conditions, but the damping characteristics are expected to be much flatter near the maximum

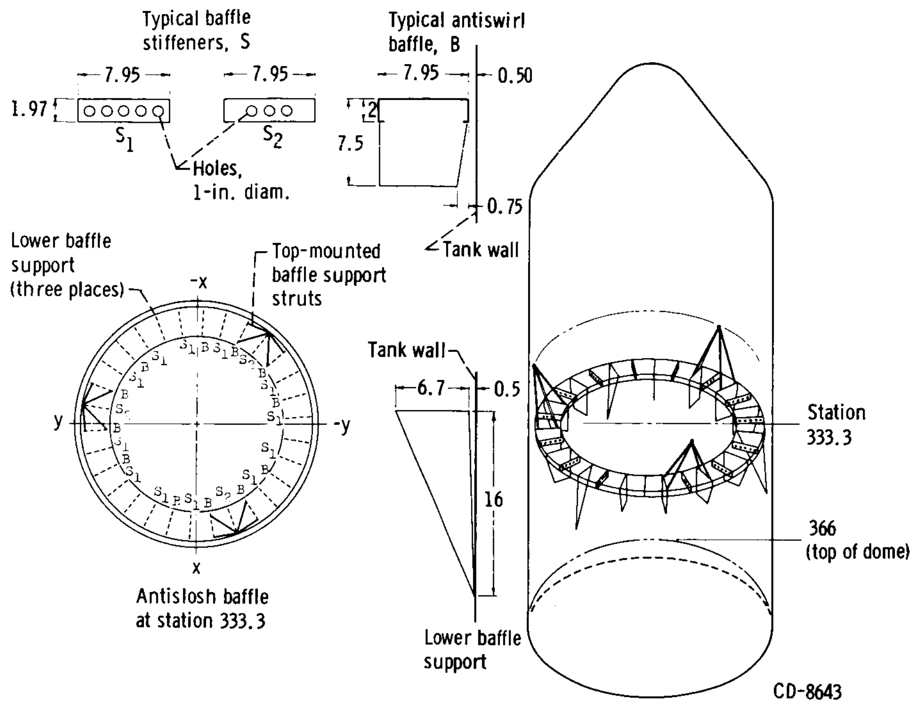

Figure 3. - AC-8 liquid-hydrogen-tank ring baffle. (All dimensions are in inches.)

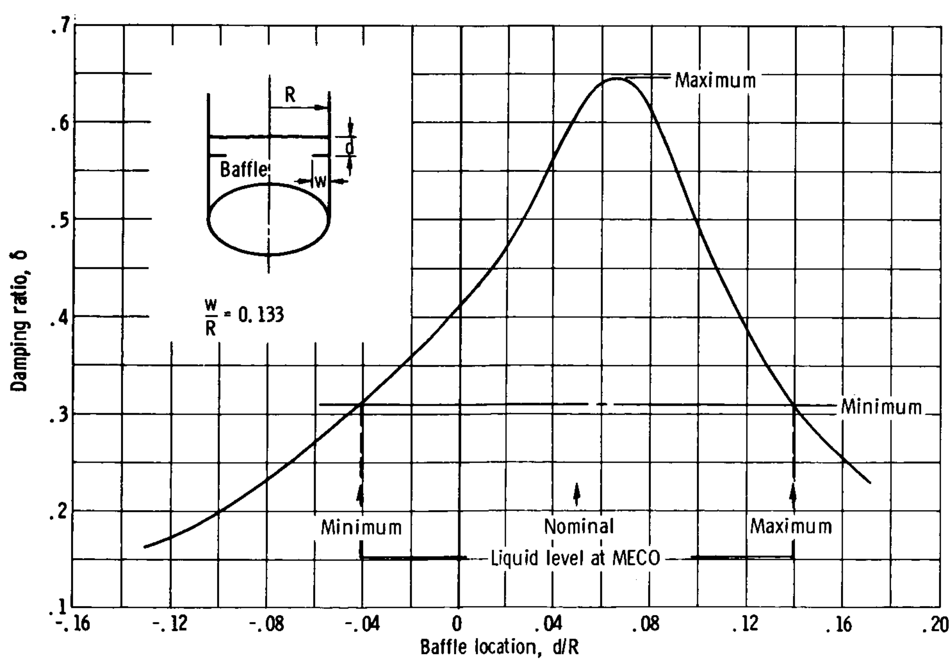

Figure 4. - Liquid-hydrogen tank baffle damping characteristics at 1 g.

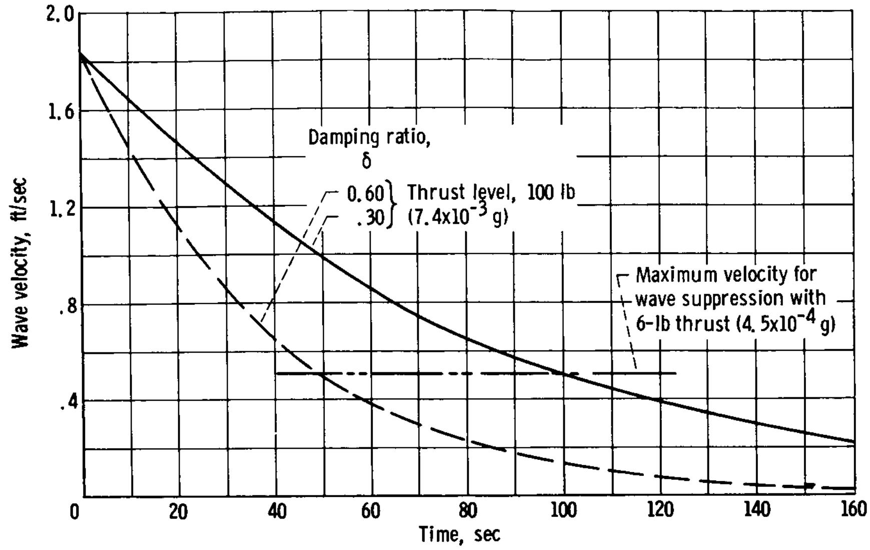

Figure 5. - Residual wave velocity with liquid-hydrogen tank baffle.

damping ratios under low-gravity conditions because of the larger wave amplitudes.

The baffle effectiveness for maximum and minimum damping ratios is shown in figure 5 for the period immediately following MECO with an applied ullage settling thrust of 100 pounds. If an initial wave velocity of 1.85 feet per second at MECO is used, then at MECO + 100 seconds the velocity would be down to 0.5 and 0.14 feet per second, respectively, for minimum and maximum damping rates. At this point the ullage thrust could be reduced to 6 pounds. A residual velocity of 0.5 feet per second with 6 pounds thrust applied to the vehicle would result in a wave height of approximately 8.6 feet, which again is well below the top of the tank.

The liquid-hydrogen tank baffle was tested in the Lewis 1/4 scale model to confirm these sloshing parameters. The only extrapolation in the effectiveness of the baffle was the damping ratio under low-gravity conditions. At present, slosh damping data under low-gravity conditions are nonexistent; therefore, the baffle design was based on data obtained under 1-g conditions. The damping ratios however, as indicated above, are expected to increase under low-gravity conditions.

Propellant Suppression and Settling

Positive position control of the propellants during the coast phase dictated the vehicle thrust schedule. This required suppressing the incipient MECO related disturbances until the residual kinetic energy was dissipated and, thereafter, only as required to maintain propellant equilibrium in a settled position. With the addition of the ring baffle and diffusers, these initial thrust requirements were greatly reduced. The equilibrium thrust

requirement, however, was dependent upon the magnitude of the surface tension forces and the possible liquid disturbances caused by vehicle attitude control corrections and thermal convective currents. For very low gravity fields this latter effect was considered negligible. Theoretically, the surface tension forces could be checked with a very low thrust of only 1.2×10^{-6} g. Vehicle related disturbances, however, are less well defined. The resulting thrust schedule conceived to support the AC-8 coast-phase mission is shown in figure 6. Configuration of the ullage thrust motors comprised four 3-pound rockets and four 50-pound rockets.

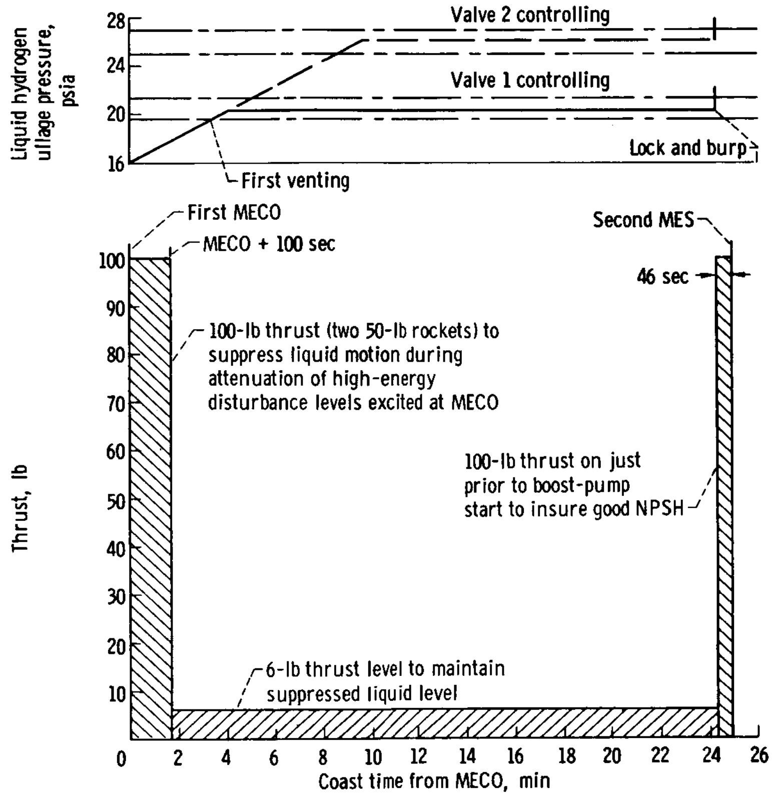

Figure 6. - AC-8 coast-phase propellant management profile.

At MECO, the required suppression of the initial fluid disturbances required a thrust of 100 pounds (two 50-lb ullage rockets), which provided a vehicle acceleration of 7.4×10^{-3} g. Then, as the transient energy was largely dissipated by the ring baffle, the 100-pound thrust was terminated at MECO + 100 seconds, and the sustaining 6-pound thrust, giving a vehicle acceleration of 4.5×10^{-4} g, maintained the propellant position through the remainder of the coast period. Just prior to boost-pump start for the second main engine burn, at second MES - 46 seconds, the 100-pound thrust was commanded on again briefly to insure propellant settling and sufficient net positive suction head (NPSH) for the boost pumps.

Evaluation and confirmation of the coast-phase propellant management on AC-8 were extremely important, and extensive instrumentation was added to the propellant tank skin and ullage as shown in figures 7 and 8. By comparison with AC-4, the AC-8 tank had temperature sensors along all four major axes instead of three, with additional sensors around the top of the forward bulkhead. The "Christmas tree" configuration shown in figure 8 was instrumented with 32 liquid-vapor sensors and 15 ullage temperature sensors to provide spatial information on temperature and liquid-vapor distribution within the hydrogen tank under both powered flight and near zero-g conditions. The liquid-oxygen tank instrumentation comprised four skin temperature measurements around the circumference of the tank at station 420 to detect any forward motion of the liquid-oxygen residual.

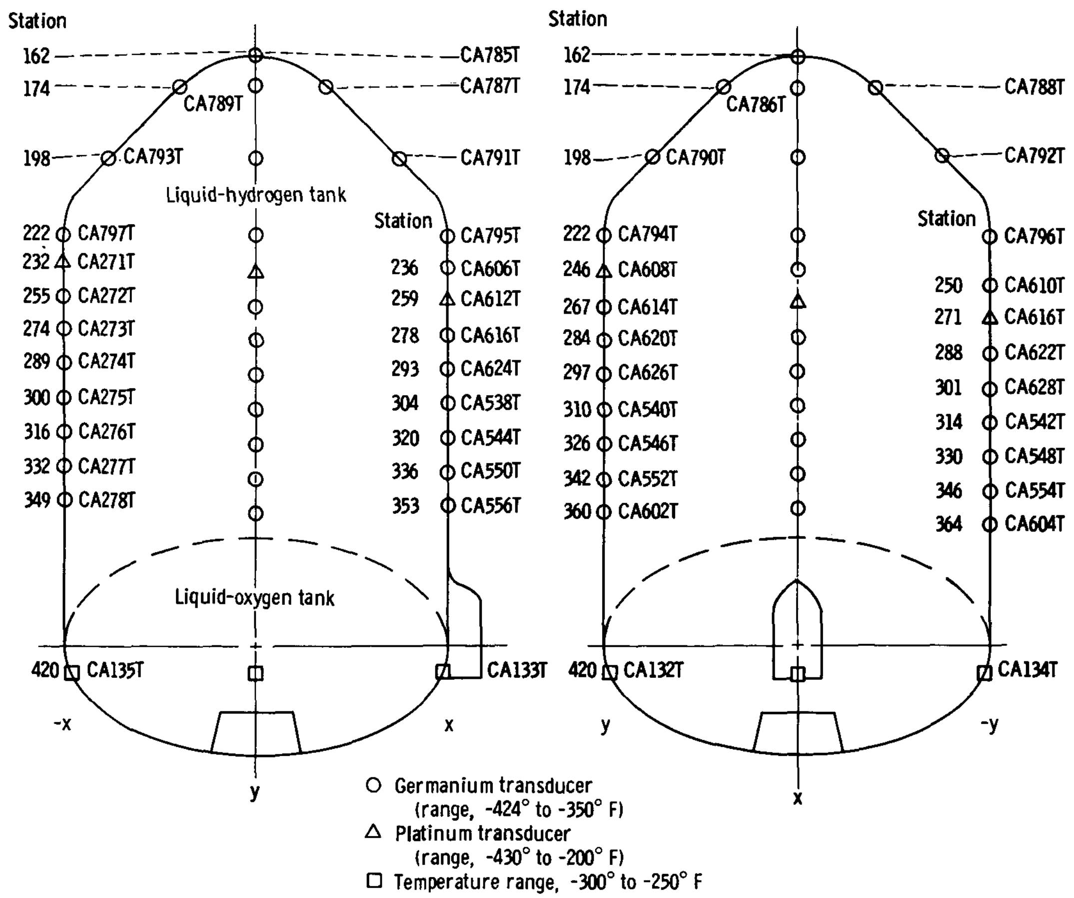

Figure 7. - AC-8 tank-skin temperature instrumentation.

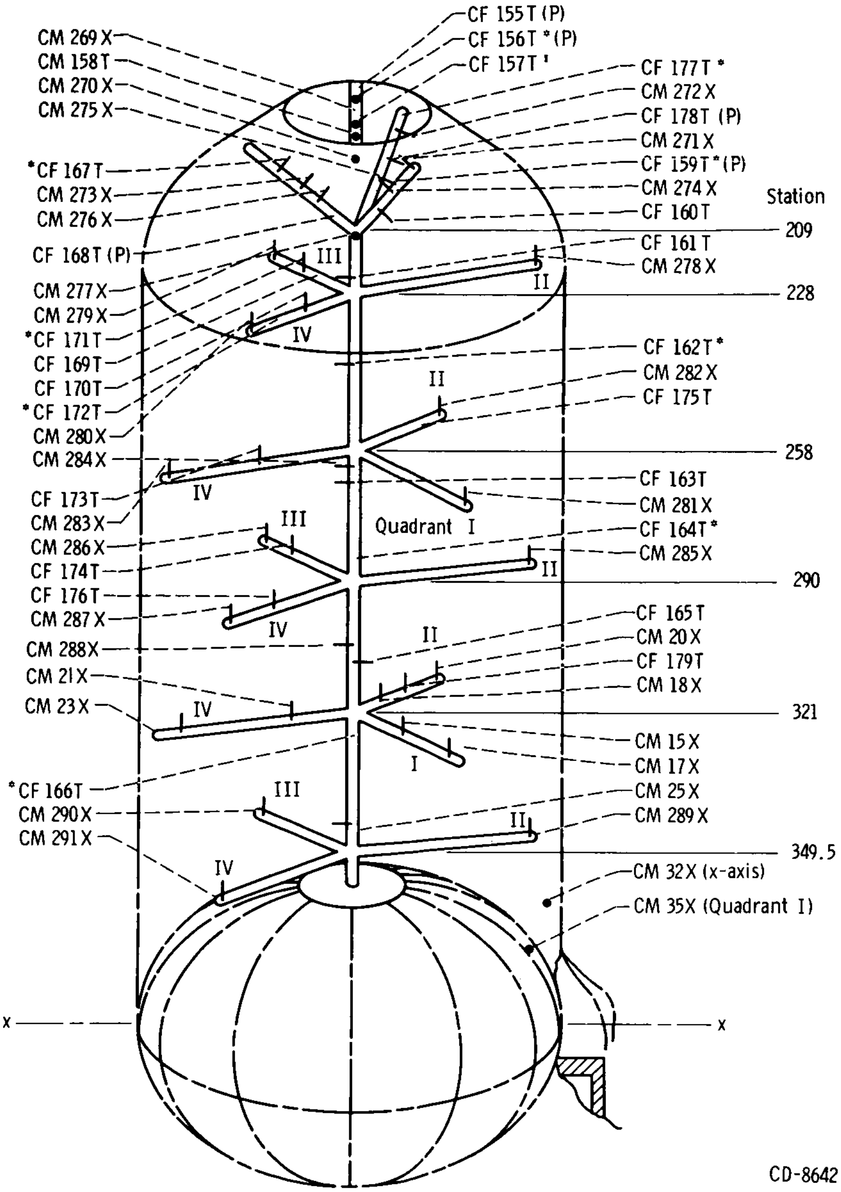

Figure 8. - AC-8 liquid-vapor sensors and ullage gas temperature sensors. Platinum transducers are indicated by (P). Asterisks indicate redundant instrumentation.

Hydrogen Venting

The hydrogen vent problems on AC-4 resulted primarily from liquid entrainment and high impingement pressures acting on the forward bulkhead, which in turn forced the vehicle out of control. The AC-4 vent system, as shown in figure 9, was, therefore, completely redesigned. The minimum ullage standpipe, flow venturi, and vent plenum were all eliminated.

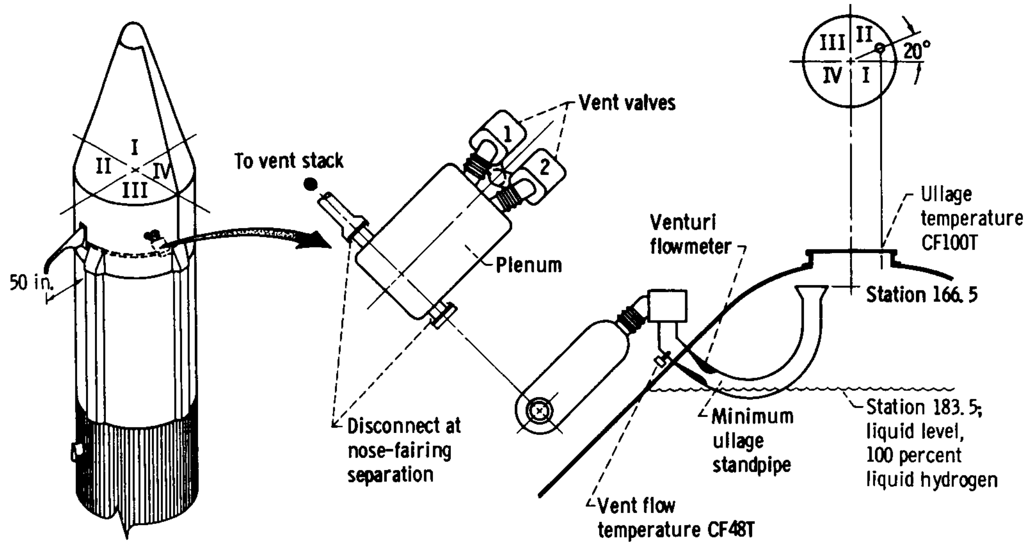

Figure 9. - AC-4 nonpropulsive vent system.

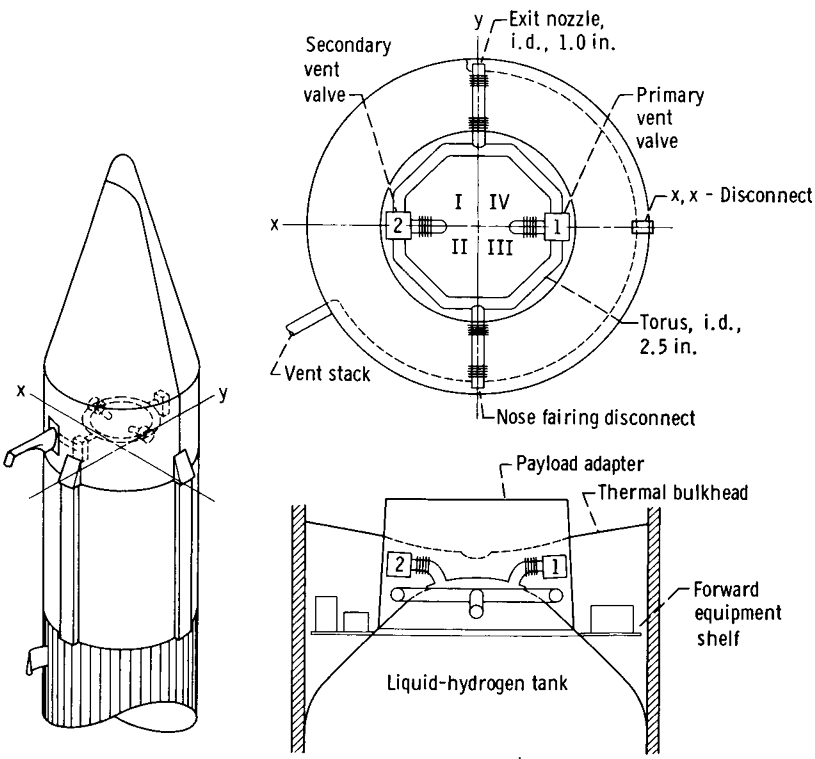

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Figure 10. - AC-8 nonpropulsive hydrogen vent.

The new AC-8 design, as shown in figure 10, vented directly out the top of the tank and into a torus assembly on the x, x-axis. This ducting was symmetrical around the top of the tank and then discharged radially in opposite directions along the y, y-axis. Exit nozzles choked the flow and were designed to limit the upstream velocity through the ducting to a Mach number of less than 0.10. Boost-phase venting through the 50-inch vent stack, with the nose fairing in place, remained unchanged. Inlet lines to the vent valves were inclined slightly to allow drainage of any liquid back into the tank. A deflector plate or baffle was also inserted below the inlet to prevent liquid sloshing directly into the vent line. The toruslike duct acted as a flow equalizer and enhanced a more complete thrust cancellation. Maximum flow rate capability of the system was about 0.7 pound per second on the ground and in excess of 1.0 pound per second after shroud separation. Qualification of this new vent system was established by extensive tests in the Lewis Space Power Chamber. The test sequence also included an evaluation of the vent valve performance.

Hydrogen venting during the coast phase would start about 9 minutes after MECO (night launch) as the ullage pressure came up to the cracking pressure of the primary vent valve. At this time the 100-pound thrust would be terminated and the propellant disturbances largely dissipated, so that the low sustained vehicle acceleration of 4.5×10^{-4} g imparted by the 6-pound ullage rockets would contain the residual propellants in a settled state. Venting therefore would develop normally and proceed without incident through the remainder of the coast phase, the tank pressure being controlled at a near constant value by the primary vent valve. Rapid depressurizations, as encountered during blowdown after vent-valve lockup periods during the boost phase, were avoided to prevent any unnecessary excitation of the liquid surface. The continuous venting thus assured good pressurization control, and, with the propellants properly settled in the bottom of the tank, engine restart after the coast period would be possible.

The concluding vehicle reorientation and retromaneuver after second MECO would not experience any hydrogen venting. Execution of this maneuver through start of propellant blowdown through the engine would be completed before the tank pressure again reached the cracking pressure of the primary vent valve.

COAST-PHASE ATTITUDE CONTROL

Design Criteria

Design improvements in the attitude control system for the AC-8 two-burn mission were based upon considerations of vehicle control requirements, control margin, and system redundancy. Mission control requirements can be reasonably well defined, but

disturbance torques caused by jet impingement forces are less well known and an extra margin makes allowance for uncertainty. System redundancy also enhances mission success by providing a secondary backup in event of a failure in the primary system.

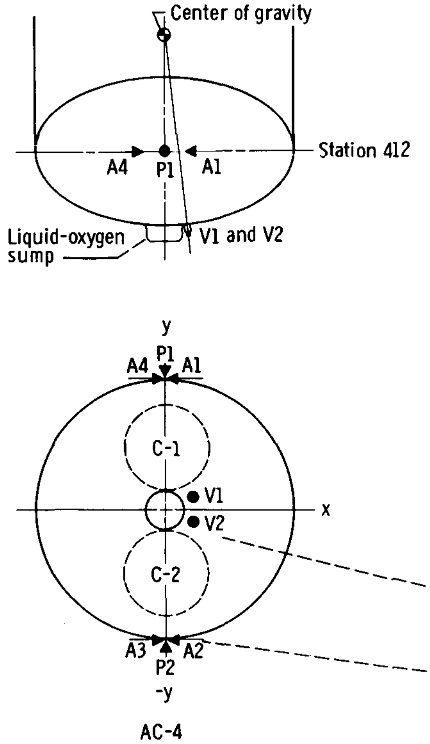
The mission control requirement of the attitude control system, aside from normal vehicle stabilization during orbital coast periods, was to perform the retromaneuver after spacecraft separation. This maneuver comprised rotation of the Centaur to a new vector 180° to the injection velocity vector, and then the application of retrothrust (blowing down residual propellants through the engines) to increase separation distance. Proper execution of the complete maneuver was bounded by maximum vehicle turning rates, due to structural considerations, and by available time after MECO prior to hydrogen tank venting. Eliminating any possibility of thrust unbalance due to hydrogen venting eases the requirements on the control system. The retromaneuver profile was conservatively based on having 300 seconds of post MECO nonventing time, and the autopilot channel selector limit was set to limit vehicle rotation rate to 1.6° per second. This allowed ample time to reorient the vehicle and initiate the retrothrust phase of the maneuver before the tank pressure reached the vent valve relief pressure.

In addition to the basic mission control requirements, firing the control rockets produces sizeable disturbance torques and related cross-coupling effects that must be corrected. The cross-coupling effects were secondary attitude errors excited in other than the primary control plane by the jet exhaust plumes impinging against surrounding structure or components. These disturbances degrade the dynamic stability and increase the duty cycle by requiring additional engines to fire to restore vehicle attitude. These impingement forces are difficult to predict and have consistently been underestimated on previous flights; however, they have not exceeded the control system capability.

The torque capability of the system for the AC-8 flight then was based on a 5:1 margin, or 20 percent duty cycle, using the maximum expected disturbances. This capacity would allow the disturbance torque to double without exceeding a 40-percent duty cycle. For AC-8 a maximum disturbance torque of 58 inch-pounds in roll is predicted due to impingement from the 50-pound ullage rockets. The control system could handle a 346-inch-pound torque correction.

AC-8 Attitude Control System

The uprated engine configuration for attitude control and propellant suppression conceived for AC-8 is shown in comparison with the AC-4 configuration in figure 11. The attitude control clusters were relocated closer inboard on the aft bulkhead and inside of the interstage adapter at station 432. The A and P engines were uprated from 1.5 and 3.0 pounds to 3.5 and 6.0 pounds of thrust, respectively. The A engines were also



Engine	AC-4		AC-8	
	Thrust, lb	Function	Thrust, lb	Function
A1	1.5	Attitude control	3.5	Attitude control
A2	1.5		3.5	
A3	1.5		3.5	
A4	1.5		3.5	
P1	3.0	Attitude control	6.0	Attitude control
P2	3.0		6.0	
S1	---		3.0	Propellant settling and attitude control
S2	---		3.0	
S3	---		3.0	
S4	---		3.0	
V1	2	Propellant settling	50	Propellant settling and attitude control
V2	2		50	
V3	---		50	
V4	---		50	

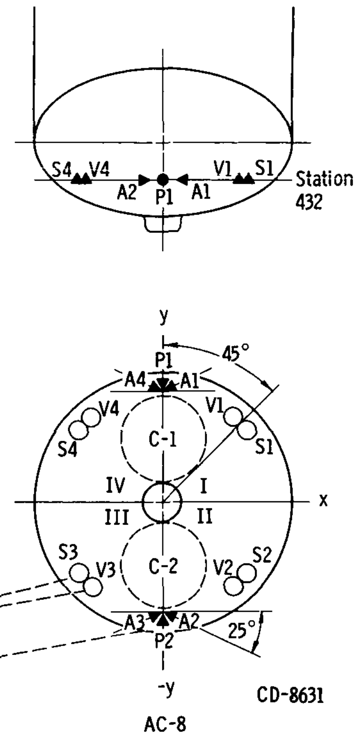


Figure 11. - AC-4 and AC-8 coast-phase attitude control systems.

canted outboard 25° to reduce impingement forces against the aft bulkhead. The two 2-pound ullage settling motors, as used on AC-4, were eliminated. Instead, four clusters, comprising one 50-pound and one 3-pound motor, were used for combined attitude control and propellant settling requirements during the coast phase and retromaneuver. These clusters were also mounted on the aft bulkhead at station 432, but in a symmetrical position 45° off the major axes in each quadrant.

The system logic for the new engine configuration integrated the 50- and 3-pound propellant settling motors with the attitude control system for optimum as well as backup control. Symmetrical thrust for the 100- and 6-pound propellant settling and retention periods was effected by firing the respective 50- or 3-pound engines in a "half-on" mode. Engines 2 and 4 were prime, but the system logic could switch the firing sequence if required for pitch and yaw control. The attitude control system provided roll control exclusively and redundant pitch and yaw control. The 3-pound engines were off during the 50-pound half-on mode, but the 50-pound engines were in a "separate-on" mode, with a slightly higher threshold, during the 3-pound half-on period to provide backup attitude control capability.

The Centaur reorientation and retromaneuver after spacecraft separation were also modified to reduce the possibility of spacecraft contamination by the jet exhaust from the peroxide engines and the residual propellants blowing down through the main engines.

Following spacecraft separation the attitude control engines rotated the Centaur 180°, but at the nominal 90° rotation point, the 50-pound engines fired in the half-on mode for 20 seconds to thrust the vehicle laterally away from the spacecraft. This minimized contamination of the spacecraft with the peroxide jet exhaust, and the earlier acceleration also effected a greater spacecraft separation distance prior to the final retrothrust obtained by blowing down the residual propellants through the main engines. It was also intended that this maneuver be completed before the hydrogen tank pressure reached the cracking pressure of the high-range vent valve. However, should venting occur, the balanced thrust vent system would cancel out the vent thrust forces and not impose any additional requirement on the attitude control system.

The total two-burn mission profile imposed a stringent requirement on the hydrogen peroxide supply and required a maximum tankage of 235 pounds. Peroxide requirements were not necessarily increased because of the larger engines, and with the A engines canted outboard, to reduce impingement forces, the requirements would be eased to give a slightly greater margin. Actually the propellant used to balance a particular external torque is independent of the thrust level of the jet; therefore, with a higher thrust level, recovery is merely effected in less time. The only penalty was the weight of six more motors and new mounting brackets (about 20 lb) to make the 14-jet configuration.

CONCLUSIONS

The two-burn mission for the AC-8 Atlas-Centaur vehicle comprises a very valuable experiment relating to the problems of low-gravity propellant behavior and verification of design concepts to effect a successful coast-phase propellant management system. Configuration of the propellant management system is the outgrowth of extensive test programs and the results of an earlier coast-phase experiment on the AC-4 vehicle. Tank baffles and diffusers have been employed to suppress and dissipate residual liquid energy in the propellant tanks. The venting system, to control propellant tank pressure, has been designed to expel the boiloff gas in a nonpropulsive manner. Also, the propellants are to be retained in a settled position by a carefully controlled thrust schedule throughout the coast interval.

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